The contribution by Domenico Pacini to the Cosmic Ray Physics

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Between 1900 and 1913 several people were investigating about the unknown radiation, later identified as Cosmic Rays. Several experimentalist tried to identify the origin of this radiation and in particular Victor Franz Hess, Theodor Wulf and Domenico Pacini. Among them Domenico Pacini had a crucial role to address the answer to the origin of this radiation in the right way, and V.F. Hess performed the complete set of measurements that definitively excluded an origin connected to the soil radioactive elements. However the most interesting and may be surprising point it that these pioneers defined 1 century ago the three experimental lines to study the Cosmic Rays: from space, on ground and underground and using only electroscopes. Domenico Pacini in particular may be considered the pioneer of the underground measurements on Cosmic Rays and Hess with his set of systematic measurements with balloon flights, originated the air-space studies on Cosmic Rays.

1. Introduction

This work want to remember the contribute to the discovery of Cosmic Rays by Domenico Pacini, that exactly 1 century ago, around 1910-1911, performed the first underground measurements of the "penetrating radiation", as the Cosmic Rays were called at that time.

The measurements by Domenico Pacini were perfectly known in all the world at that time and cited by several older reviews about the Cosmic Rays[1,2,3,4,5] and in particular Wolfendale[1] noted that the first one to suggest a non-radioactive origin of Cosmic Rays was Pacini, whose importance is going to be almost forgotten by latest reviews on this matter[6]most of the actual and the community of people working on Cosmic Rays.

For this reason and approaching to the european celebrations of the centenary of the discover of Cosmic Rays, this review, together others that are in preparation [7,8,9,10], wants to give evidence to the contribution by Pacini and other experimentalists that in every case originated the actual ways to study the Cosmic Rays, and that together the set of measurements by V.F.Hess, completed the puzzle about the origin of this radiation.

2. First evidences of a unknown radiation

It was well known since 1785 by Coulomb[11] that electroscopes spontaneously discharge by the action of the air. After the discovery of the radioactivity in 1896 by Bequerel[12] it was well understood that in presence of radioactive elements charged electroscopes promptly discharged and the discharge rates were used, at the beginning of the 20th century, to infer the level of radioactivity. So the logical conclusion about the spontaneuos discharge of electroscopes in air is that the presence of radioactive elements on the soil produces charged particles that acts on the electroscopes.

Therefore a huge effort to improve the instruments, understand and identify the origin and the nature of the unknokn radiation, involved many people during the beginnings of 1900. In particular, Wilson, Elster and Geitel [13,14] modified the electroscope basic drawings to improve the electroscope insulation and shielding. As a result, they could make quantitative measurements of the rate of spontaneous electroscope discharge. They independently concluded that such a discharge was due to ionizing agents coming from outside the vessel.

The obvious questions concerned the nature of

such radiation, and whether it was of terrestrial or extra-terrestrial origin. For example in 1900 Wilson[13] tentatively suggested that the ionizing angent may be a penetrating radiation of extra-terrestrial origin.

The simplest hypothesis however was that its origin was related to radioactive materials, hence terrestrial origin was a commonly accepted assumption. The experimental demonstration of such hypothesis however was difficult to probe.

In 1903 Rutherford and Cook [15] and also McLennan and Burton [16] showed that the ionisation was significantly reduced when the closed vessel was surrounded by shields of metal kept free from radioactive impurity. Later investigations showed that the ionization in a closed vessel was due to a "penetrating radiation" partly from the walls of the vessel and partly from outside. The lot of measurements by several people at different latitudes are summarised by Kurz [17] and by Cline [18] that discuss about the origin of the radiation.

Cline[18] on 1910 summarizes in his paper the status of art at that moment, and listed the most import measurements at that time, that were mainly oriented to measure the daily variations[19] or seasonal variation[20]. Cline in the same paper cited Pacini work [21] about the daily variations of the radiation measured on the sea at Sestola in Italy, a further demonstration of the experimentalist relevance of Pacini at that time.

This Pacini's measurement was particularly remarked in Cline's paper as a first evidence of the atmosphere as the main responsable of the penetrating radiation and at the same time excluding the Sun as the main origin. Cline's conclusions of his own measurements in Canada however, were that a larger contribution of the radiation should be attributed to the soil and a negligible contribution from the Sun or the atmosphere.

Finally in the review by Kurz[17] three possible sources for the penetrating radiation are discussed: an extra-terrestrial radiation possibly from the Sun, radioactivity from the crust of the Earth, and radioactivity in the atmosphere. Kurz concludes, however, that the possibility of an extraterrestrial radiation seems to be unlikely.

It was generally assumed that large part of the radiation can be accounted as γ-rays emitted by radioactive material in the crust[23,24]. Calculations were made of how the radiation should decrease with height (see e.g. Eve [25]) and measurements were performed.

Father Theodor Wulf, a German scientist and a Gesuit priest serving in the Netherlands and then in Roma, had the idea to check the variation of radioactivity with height to test its origin. In 1909 [23] Wulf, using an improved electroscope[26] (Fig. 1) in which the two leaves had been replaced by two metalized silicon glass wires, with a tension spring made also by glass in between, first measured the ionization rate inside a cave at Valkenburg in Holland then the rate of ionization at the top of the Eiffel Tower in 1910 in Paris (300 m above ground). Supporting the hypothesis of the terrestrial origin of most of the radiation, he expected to find at the top a much smaller ionization than on the ground. The rate of ionization found, however, a decrease too small to confirm the hypothesis. He concluded that, in comparison with the values on the ground, the intensity

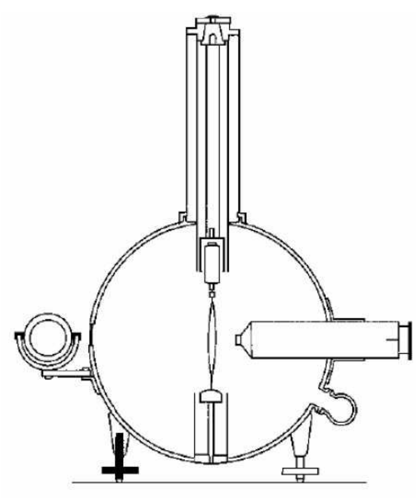

Figure 1. The Wulf electroscope.

of radiation “decreases at nearly 300 m [altitude] not even to half of its ground value”; while with the assumption that radiation emerges from the ground there would remain at the top of the tower “just a few percent of the ground radiation” [23].

Wulf’s observations were of great value, because he could take data at different hours of the day and for many days at the same place. For a long time, Wulf’s data were considered as the most reliable source of information on the altitude effect in the penetrating radiation. However Wulf concluded that the most likely explanation of his puzzling result was still emission from the soil.

3. Pacini contribution to the "unknown radiation" discussion

Figure 2. Domenico Pacini, picture taken from the obituary in Bari University.

The conclusion that radioactivity was mostly coming from the Earth’s crust was questioned by the Italian physicist Domenico Pacini, who compared the rate of ionization on mountains, over a lake, and over the sea [27,28]; in 1911, he made important experiments by immersing an electroscope deep in the sea [29].

Pacini[22] (Fig. 2) was born in 1878, in Marino, near Roma. He graduated in Physics in 1902 at the Faculty of Sciences of Roma University. There, for the next three years, he worked as an assistant to Professor Blaserna studying electric conductivity in gaseous media. In 1906 Pacini was appointed assistant at Italy’s Central Bureau of Meteorology and Geodynamics, heading the department that was in charge of studying thunderstorms and electric phenomena in the atmosphere. Pacini held that position until 1927, when he was upgraded to Principal Geophysicist. Finally in 1928 he was appointed full professor of Experimental Physics at the University of Bari. Pacini died of pneumonia in Roma in 1934, shortly after his marriage.

Pacini’s important results on the penetrating radiation started with studies on electric conductivity in gaseous media performed at the University of Roma during the early years of the 20th century. During 1907-1912, he performed several detailed measurements on the conductivity of air, using an Ebert electroscope to enhance the sensitivity (he could reach a sensitivity of one third of volt).

In a first period Pacini made several measurements to establish the variations of the electroscope’s discharge rate as a function of the environment. First he placed the electroscope on the ground and on the sea a few kilometers off the coast; the results were comparable. An example of the electroscopes used by Pacini is in Fig.6 taken from the paper in [31].

A summary of these results indicates, according to Pacini’s conclusions, that “in the hypothesis that the origin of penetrating radiations is in the soil, since one must admit that they are emitted at an almost constant rate (at least when the soil is not covered by remaining precipitations), it is not possible to explain the results obtained” [27].

It is clear that Pacini’s conclusion, confirmed

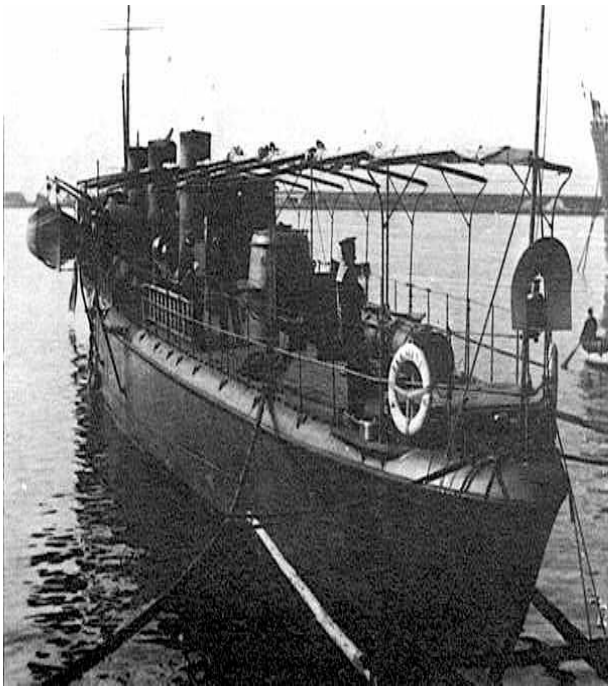

Figure 3. The cacciatorpediniere "Fulmine", used by Pacini for his measurements on the sea.

by Gockel [24], was the first that clearly affirmed the results of many experiments on radiation could not be explained by the radioactivity in the Earth's crust.

Pacini continued the investigations of radiation and developed in 1911 an experimental technique for underwater measurements[29,30]. From this point of view it's evident that Pacini was among the first scientists to think and use "underground-undersea" measurements to study what later we called Cosmic Rays. He found a significant decrease in the discharge rate when the electroscope was placed underwater. Pacini made his measurements over the sea in the Gulf of Genova[30], on an Italian Navy ship, the *cacciatorpediniere* (destroyer) "Fulmine" (Fig. 3) from the Accademia Navale di Livorno.

He reported those measurements, results, and their interpretation, in a note titled *La radiazione penetrante alla superficie ed in seno alle acque (Penetrating radiation at the surface of and in water)* [29]. In that paper Pacini wrote: "Observations carried out on the sea during the year 1910 [28] led me to conclude that a significant proportion of the pervasive radiation that is found in air had an origin that was independent of direct action of the active substances in the upper layers of the Earth's surface. ... [To prove this conclusion] the apparatus ... was enclosed in a copper box so that it could immerse in depth. ... From June 24 to June 31 [sic!] [1911], observations were performed with the instrument at the surface, and with the instrument immersed in water, at a depth of 3 meters."

With the apparatus at the surface 300 m from land, Pacini measured seven times during three hours the discharge of the electroscope, obtaining a loss of 12.6 V/hour, corresponding to 11.0 ions per second (with a RMS of 0.5 V/hour); with the apparatus at a 3 m depth in the 7 m deep sea, he measured an average loss of 10.3 V per hour, corresponding to 8.9 ions per second (with a RMS of 0.2 V/h). Consistent results were obtained during measurements at the Lake of Bracciano.

The measurement underwater was 20% lower than at the surface, consistent with absorption by water of a radiation coming from above. "With an absorption coefficient of 0.034 for water, it is easy to deduce from the known equation $I/I_0 = \exp(-d/\lambda)$, where d is the thickness of the matter crossed, that, in the conditions of my experiments, the activities of the sea-bed and of the surface were both negligible. The explanation appears to be that, due to the absorbing power of water and the minimum amount of radioactive substances in the sea, absorption of radiation coming from the outside happens indeed, when the apparatus is immersed." Pacini concluded [29]: "[It] appears from the results of the work described in this Note that a sizable cause of ionization exists in the atmosphere, originating from penetrating radiation, independent of the direct action of radioactive substances in the soil."

By the way, in 1910 Pacini[31] looked for a possible increase in radioactivity during a passage of the Halley's comet (and he found no effect of the comet itself). Similar sea measurements were

performed by Simpson and Wright in 1911[32] showed a relevant ionization over the sea, a result not accounted by the soil radioactivity, since sea water should contain only a minor fraction of radioactive elements.

3.1. Hess and the balloon measurements

The need for balloon experiments became evident to clarify Wulf's observations on the effect of altitude (at that time and since 1885, balloon experiments were anyway widely used for studies of the atmospheric electricity). The first balloon flight with the purpose of studying the properties of penetrating radiation was arranged in Switzerland in December 1909 with a balloon called Gotthard from the Swiss aeroclub. Alfred Gockel, professor at the University of Freiburg, ascending in a balloon up to 4500 m above sea level (a.s.l.) during three successive flights, found [33,34] that the ionization did not decrease with height as expected on the hypothesis of a terrestrial origin. Gockel confirmes the conclusion of Pacini and concludes "that a non-negligible part of the penetrating radiation is independent of the direct action of the radioactive substances in the uppermost layers of the Earth" [34]. In spite of Pacini's conclusions, and of Wulf's and Gockel's puzzling results on the dependence of radioactivity on altitude, physicists were however skeptical about the hypothesis of a non-terrestrial origin.

The situation was cleared up thanks to a long series of balloon flights by the Austrian physicist Victor Hess (Fig.4), who established the extra-terrestrial origin of at least part of the radiation causing the observed ionization.

Figure 4. Victor Franz Hess.

Hess was born in 1883 in Steiermark, Austria, and he took his doctor's degree in 1910 in Graz. After graduation he was assistant under professor Meyer at the Institute of Radium Research of the Viennese Academy of Sciences, where he performed most of his work on cosmic rays, and in 1919 he became Professor of Experimental Physics at the Graz University. Hess was on leave of absence from 1921 to 1923 and worked in the United States, where he took a post as Director of the Research Laboratory of the United States Radium Corporation, at Orange (New Jersey). In 1923 he returned to Graz and in 1931 he moved to Innsbruck as professor. In 1936 Hess was awarded the Nobel Prize in physics for the discovery of Cosmic Rays. After moving to USA in 1938 as professor at Fordham University, Hess became an American citizen in 1944, and lived in New York until his death in 1964. Hess started his experiments by studying Wulf's results, and knowing the detailed predictions by Eve[35] on the coefficients of absorption for radioactivity in the atmosphere. Eve wrote that, if one assumed a uniform distribution of RaC on the surface and in the uppermost layer of the Earth, "an elevation to 100 m should reduce the [radiation] effect to 36 percent of the ground value". Hess added: "This is such a serious discrepancy [with Wulf's results] that its resolution appears to be of the highest importance for the radioactive the-

ory of atmospheric electricity" [36]. Since in the interpretation of Wulf's and Gockel's results the absorption length of the radiation (at that time identified mostly with gamma radiation) in air entered crucially, Hess decided first to improve the experimental accuracy of the Eve's result by "direct measurements of the absorption of gamma rays in air" [37]. He used probes of about 1 g $RaCl_2$ at distances up to 90 m, and obtained an absorption coefficient consistent with Eve. Hence the contradiction of Wulf's results remained; Hess concluded that "a clarification can only be expected from further measurements of the penetrating radiation in balloon ascents" [37].

Figure 5. Historical photograph of Hess preparing for a balloon flight.

Hess continued his studies with balloon observations (Fig. 5). The first ascension took place on August 28, 1911. "[T]he balloon" Radetzky" of the Austrian aeroclub with Oberlutnant S. Heller as pilot and me as sole passenger was lifted" [37]. The ascension lasted four hours and went up to a height of 1070 m above ground. A second ride in another balloon ("Austria") during the night of 12 October 1911 went up to 360 m above ground. During both balloon flights, the intensity of the penetrating radiation was measured to be constant with altitude within errors. From April 1912 to August 1912 Hess had the opportunity to fly seven times with three instruments (two with thick walls and one with thin walls, to disentangle the effect of beta radiation). In the final flight, on August 7, 1912, he reached 5200 m. To his surprise, the results clearly showed that the ionization, after passing through a minimum, increased considerably with height.

"(i) Immediately above ground the total radiation decreases a little. (ii) At altitudes of 1000 to 2000 m there occurs again a noticeable growth of penetrating radiation. (iii) The increase reaches, at altitudes of 3000 to 4000 m, already 50% of the total radiation observed on the ground. (iv) At 4000 to 5200 m the radiation is stronger [more than 100%] than on the ground" [36].

Hess concluded that the increase of the ionization with height must be due to a radiation coming from above, and he thought that this radiation was of extra-terrestrial origin. He also excluded the sun as the direct source of this hypothetical penetrating radiation because of no day-night variation. Hess finally published a summary of his results in Physikalische Zeitschrift in 1913 [38], a paper which reached the wide public.

The results by Hess were later confirmed by Kolhörster [39] in a number of flights up to 9200 m. An increase of the ionization up to ten times that at sea level was found. The absorption coefficient of the radiation was estimated to be 10^{-5} per cm of air at NTP. This value caused great surprise as it was eight times smaller than the absorption coefficient of air for gamma rays as known at the time. Kolhörster continued his investigations using newly constructed apparatuses and made measurements at mountain altitudes with results published in 1923[40] in agreement with earlier balloon flights. There were, however, also negative attitudes in Europe against

an extra-terrestrial radiation. Hoffmann, using newly developed electrometers, concluded [41] that the cause of the ionisation was radioactive elements in the atmosphere. Similar conclusions were reached by Behounek [42] and for several years this convinction was no more discussed.

4. Toward the final understanding of the origin of the radiation

After the war, the focus of the research moved to the US. Millikan and Bowen [43] developed a low mass (about 200 g) electrometer and ion chamber for unmanned balloon flights using data transmission technology developed during World War I. In balloon flights to 15,000 m in Texas they were surprised to find a radiation intensity not more than one-fourth the intensity reported by Hess and Kolhörster. They attributed this difference to a turnover in the intensity at higher altitude, being unaware that a geomagnetic effect existed between the measurement in Europe and Texas. Thus, Millikan believed that there was no extraterrestrial radiation. As reported to the American Physical Society in 1925 Millikan's statement was "The whole of the penetrating radiation is of local origin".

In 1926, however, Millikan and Cameron [44] carried out absorption measurements of the radiation at various depths in lakes at high altitudes. Based upon the absorption coefficients and altitude dependence of the radiation, they concluded that the radiation was high energy gamma rays and that "these rays shoot through space equally in all directions" calling them "cosmic rays".

Millikan was handling with energy and skill the communication with the media, and in the US the discovery of Cosmic Rays became, according to the public opinion, a success of American science. Millikan argued that the radiations are "generated by nuclear changes having energy values not far from [those that they recorded] in nebulous matter in space." Millikan then proclaimed that this cosmic radiation was the "birth cries of atoms" in our galaxy. His lectures drew considerable attention from, among others, Eddington and Jeans, who struggled unsuccessfully to describe processes that could account for Millikan's claim. It was generally believed that the cosmic radiation was gamma radiation because of its penetrating power (one should remember that the penetrating power of relativistic charged particles was not known at the time). Millikan had put forward the hypothesis that the gamma rays were produced when protons and electrons form helium nuclei in the interstellar space.

A key experiment, which would decide the nature of Cosmic Rays (and in particular if they were charged or neutral), was the measurement of the dependence of cosmic ray intensity on geomagnetic latitude. Important measurements were made in 1927 and 1928 by Clay [45] who, during two voyages between Java and Genova, found that the ionisation increased with latitude. No such variation was expected if the radiation was a gamma radiation, but Clay did not draw a firm conclusion as to the nature of the cosmic radiation. Clay's work was disputed by Millikan.

With the introduction of the Geiger-Muller counter in 1928, a new era began and soon confirmation came that the cosmic radiation is indeed corpuscular. Kolhörster introduced the coincidence technique. Bothe and Kolhörster [46] concluded that the cosmic radiation is mainly or fully corpuscular, but still Millikan did not accept this view.

In 1932 Compton carried out a world-wide survey to settle the dispute. He then reported [47] that there was a latitude effect, that Cosmic Rays were charged particles and that Millikan was wrong. Millikan attacked strongly Compton, but after repeating his experiment in 1933 he admitted that there was a latitude effect and that the Cosmic Rays must be (mostly) charged particles. However, it would take until 1941 before it was established in an experiment by Schein [48] that Cosmic Rays was mostly protons.

The 1936 Nobel Prize in Physics was shared by professor V.F. Hess for the discovery of Cosmic Rays and dr. C.D. Anderson for the discovery of the positron.

Professor H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences, said in his speech at the Nobel award ceremony in 1936: "[A] search was made throughout nature for radioactive sub-

stances [by several scientists]: in the crust of the Earth, in the seas, and in the atmosphere; and ... the electroscope was applied. Radioactive rays were found everywhere, whether investigations were made into the waters of deep lakes, or into high mountains. ... Although no definite results were gained from these investigations, they did show that the omnipresent radiation could not be attributed to radiation of radioactive substances in the Earth's crust...The mystery of the origin of this radiation remained [however] unsolved until Prof. Hess made it his problem. ... With superb experimental skill Hess perfected the instrumental equipment used and eliminated its sources of error. With these preparations completed, Hess made a number of balloon ascents... From these investigations Hess drew the conclusion that there exists an extremely penetrating radiation coming from space which enters the Earth's atmosphere.

5. Conclusions

The history of Cosmic Rays discovery may be divided into two era: in the early stage a lot of people contributed to the understanding of the origin and the characterization of the radiation as penetrating radiation. Pacini, Wulf, Gockel and Hess among the others, contributed both to the developement of the instruments to detect the effects and characterize the unknown penetrating radiation.

Moreover this people identified the basic three ways to study Cosmic Rays, i.e. underground-undersea measurements, ground and balloon-borne or space measurements, techniques that really were applied only about 40 years later when the detectors evolved towards the particle physics. In every case the conclusion by the Royal Swedish Academy of Sciences can be repeated: the discovery of Cosmic Rays has opened new areas for experimental and theoretical physics of greatest significance for our understanding of the structure and origin of matter and that Hess measurements established clearly that the radiation had an extraterrestrial origin.

We hope that this note will establish correctly the effort of many people involved in the discovery of Cosmic Rays about 100 years later the most relevant set of measurements that removed the ambiguity about the origin: in particular D. Pacini with his underground measurements and V.Hess with his balloon measurements, have clearly excluded the soil radioactivty as the main reason for the penetrating radiation, and posed the basis for the moder cosmic ray physics.

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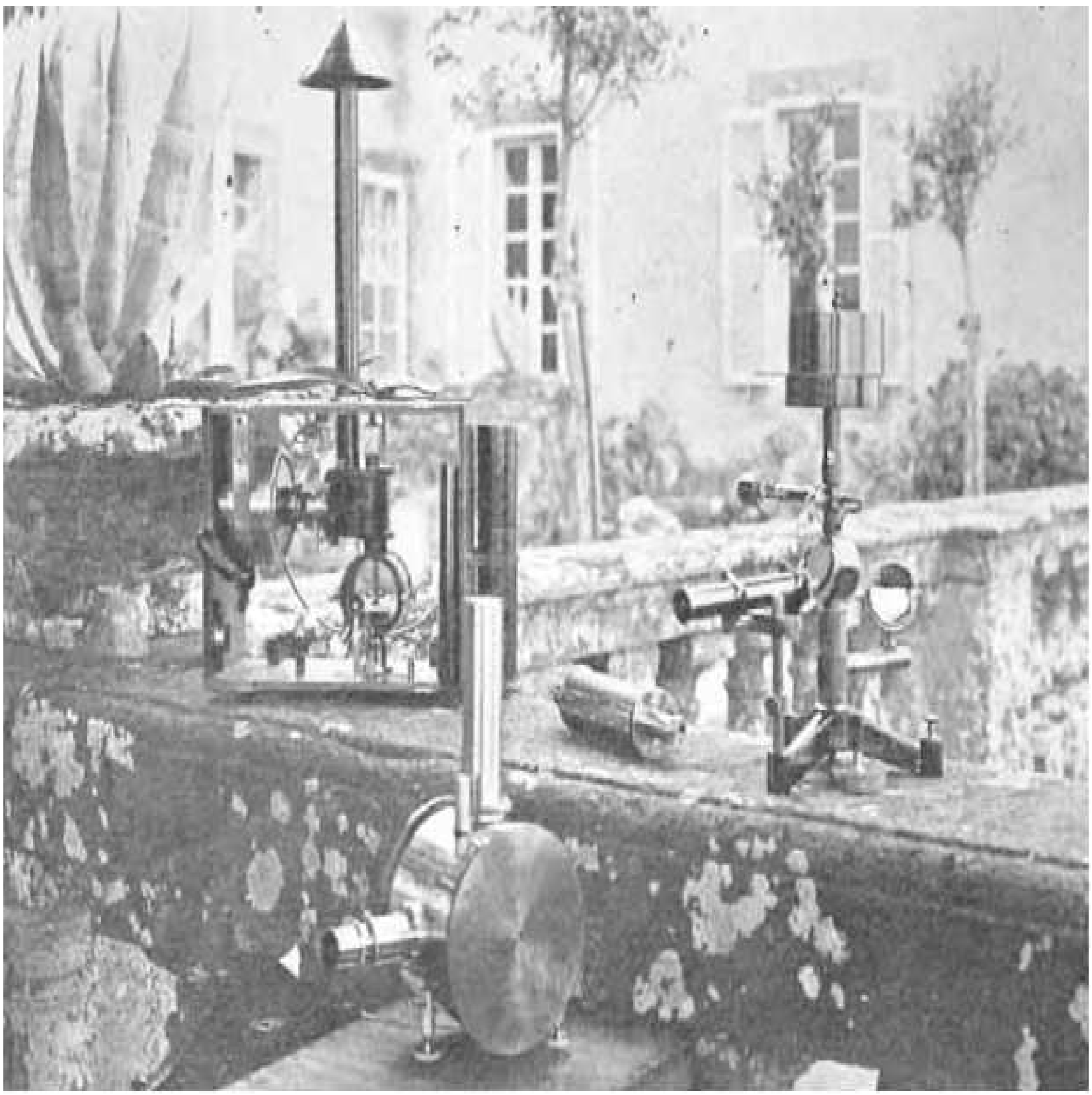

Figure 6. Pacini's electroscopes, picture included in [29].